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Simulation of Fog Oil Deposition During Military Training Operations

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Abstract: In this study we evaluate the ability to simulate deposition of a fog oil (Standard Grade Fuel Number 2 or SGF2) obscurant on the ground using the SCIPuff aerosol transport model. Model results are compared to actual deposition of fog oil measure on the ground during two military training exercises in Alaska. One exercise took place during late summer; the other occurred during midwinter.

The results show that SCIPuff can be used to give a general picture of the spatial deposition of fog oil by successfully reproducing the overall trends of the field data and predicting the deposition to within an order of magnitude or better. Improved predictive capability might be realized using more sophisticated flow solvers employing computational fluid dynamics (CFD) and large eddy simulation (LES) methods. However, use of CFD and LES would increase significantly the computational expense required.

This study shows that model results are sensitive to the aerosol droplet size distribution used and that there appears to be some dependency of this size distribution on air temperature or fog oil used (pure SGF2 vs. SGF2:diesel mix). To improve the predictive modeling capability of aerosol transport models, it is recommended that further work be accomplished to quantify the environmental and mixture effects on the airborne fog oil droplet size distribution. In lieu of this information, an estimate of the deposition, good to within about an order of magnitude, can be obtained using a lognormal droplet size distribution with a mean droplet size of 1 μm and variance of 1.7.

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Preface

This report was prepared by Robert B. Haehnel, Research Mechanical Engineer, Terrestrial and Cryospheric Sciences Branch, US Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire.

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This report was prepared under the general supervision of Dr. Justin B. Berman, Chief, Research and Engineering Division, CRREL; Dr. Lance D. Hansen, Deputy Director, CRREL; and Dr. Robert E. Davis, Director, CRREL.

At the time this report was published, Colonel Gary E. Johnston was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

Fog oil generators are commonly used in military operations to produce a battlefield obscurant of dense grey aerosols. The generators vaporize Standard Grade Fuel Number #2 (SGF2) in a pulse jet mechanical generator to produce a “dense, grey to white, suspended, smoke-like plume” (Douglas et al. 2006). The fog oil aerosols eventually settle to the ground, and as a result, training with fog oil may have negative environmental impacts on training lands.

The objective of this effort is to evaluate the ability to simulate the deposition of fog oil aerosol on the ground during typical military training operations using an available simple transport model. Data documenting the deposition of fog oil were obtained during four training events at Fort Greely, Alaska, and Fort Wainwright, Alaska. The four individual exercises and the methods used to measure fog oil aerosol deposition are described in detail by Douglas et al. (2006). Two of these four events, named Events 3 and 4 by Douglas et al. (2006), were simulated. The other two events (Events 1 and 2) were not simulated because the sources were moving throughout the training exercise. Simulation of moving sources requires detailed information about the time-dependent location of the sources, but these data were not recorded. Also, the exposure time of the filters was not always well known, and the meteorological conditions for these events were not sufficiently documented.

In this report, I present a comparison between the deposition of oil fog on the ground during Events 3 and 4 and the model results obtained by simulating these events. The potential application of the modeling capability for predicting fog oil deposition during planned training exercises is discussed. The results from this study—combining field measurements and modeling to predict fog oil aerosol deposition—also may be applicable toward investigations of the transport and deposition of other aerosol contaminants.

2 Methods

The software program SCIPuff (Second-order Closure Integrated Puff; Sykes and Gabruk 1997, Sykes et al. 1999) was used to model the transport and deposition of fog oil within the training area¹. This model is the underlying computational engine for HPAC (Hazard Prediction and Assessment Capability) developed for the Defense Threat Reduction Agency (DTRA)². Though HPAC could have been used to simulate these events, it was easier to run the simulations using SCIPuff because it was simpler to specify the droplet size distribution and incorporate the meteorological data that were measured during the exercises.

Fog oil “smoke” is generated by volatilizing Standard Grade Fuel #2 (SGF-2) by blowing it through a heated manifold. For the field tests, M157A2 fog oil aerosol generators (Figures 1 and 2) were mounted on High-Mobility Multipurpose Wheeled Vehicles (HMMWVs). The generators can be operated in either a static position with the vehicle parked or as a mobile generator with the vehicle in motion. Each generator consumes roughly 40 gallons (151 L) of fog oil per hour, with maximum and minimum rates ranging from 25 to 50 gallons (95 to 190 L) per hour, respectively.

During a typical fogging event, a dense white aerosol cloud is emitted from the generator. The cloud disperses in all directions as it leaves the generator and travels downwind. After ten to fifteen minutes of fogging, the plume can be more than a kilometer long and hundreds of meters wide and tall.

SCIPuff is a Gaussian puff model formulated to capture convection and turbulent diffusion of a particulate or gaseous cloud. The aerosol dispersion is handled using a Lagrangian frame of reference; individual puffs of the aerosol—of initial mass per unit volume—are released from the source(s) and then tracked as they are convected by the wind. The rate of release of the puffs can vary to simulate time-dependent changes in the amount of aerosol released from the source(s). These puffs are also al-

¹ SCIPuff version 1.221 is the version used in this study and is available for download at <http://www.titan.com/products-services/336/index.html?docID=336>.

² HPAC version 4.04 is the version used in this study and is available upon request from L-3 Communications, Titan Group.

lowed to stretch in three dimensions, simulating diffusion of the puff as it is convected. Logic is employed in the algorithm to handle splitting and recombination of puffs as they stretch and collide. Further details of the algorithm are given in Sykes et al. (1999). SCIPuff can reproduce the effects of terrain (terrain data) on dispersion. However, this feature was not used in this study because the topography where the exercises were conducted was generally flat.

The velocity profile at the surface can either be specified by providing surface observations (velocity as a function of height) as part of the meteorological record, or is computed as part of the simulation. The latter method was used for these simulations because the only available surface wind observations were measured at the 3-m elevation. Using this option, the boundary layer profile was computed assuming a logarithmic velocity profile over a rough surface. The roughness of the surface is characterized by the aerodynamic roughness height, Z_o (see Table 1).



Figure 1. Foggers in operation.



Figure 2. Close-up of an M157A2 fog oil aerosol generator during operation.

3 Details of the Model Runs

What follows is a summary of each event simulated and the detailed information needed to set up each model run to simulate the two events.

Details of Events 3 and 4 are given in Douglas et al. (2006).

Event 3 (31 January 2002)

This exercise was conducted at Firebird Landing Zone, Fort Wainwright, Alaska. The average air temperature was -15°C with clear skies. During this event, four fog oil generators, mounted on three separate HMMWVs, were used. The HMMWVs were side by side and located about 5 m apart (Figure 3). The nozzles of the generators were pointed in approximately the south-southwest direction, which was *about* the same direction the wind was blowing; the wind was approximately from the north-northeast. The two end HMMWVs had only one of their two fog oil generators running, while both fog oil generators were running on the middle HMMWV. To decrease the viscosity of the fog oil for this winter exercise, a 70:30 mixture of SGF2:diesel fuel was used in the generators. The amount of this mixture used by each individual generator during this exercise was not documented, but the total consumption used by all four generators was 760 L. The duration of the exercise was 93 minutes and it started at 1342 Alaska Standard Time (AST).

A meteorological tower (Met Station) was located approximately 300 m downwind of the oil generators (Figure 3), and was used to record relative humidity, wind speed, and direction throughout the exercise.

The deposition of fog oil aerosol on the ground was measured in the field using three types of passive collection samplers that were deployed on top of the 1-m-deep snowpack (Figure 4):

1. Filters: glass microfiber filters placed on a cardboard backing that was placed on the snow surface;
2. Flowers: the flower part of a synthetic plant stalk (Figure 4), with the stem of the stalk pushed into the snowpack;

3. Leaves: the leaf part of the same synthetic plant stalks used in 2, above.

The details of the collection and analysis of the oil deposition on each of these sample surfaces are given in Douglas et al. (2006). The locations of the samplers that were deployed during the full duration of the event are shown in Figure 3.

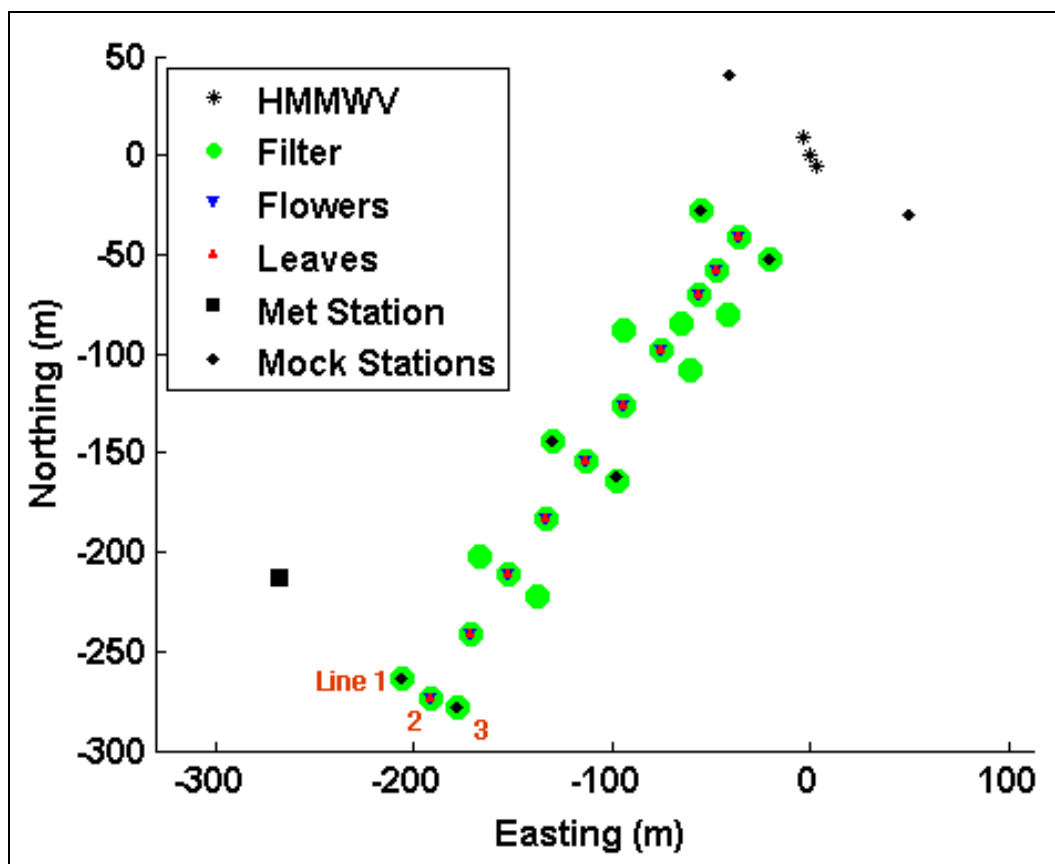


Figure 3. Site layout for Event 3 on 31 January 2002.



Figure 4. Microfiber filters and synthetic vegetation used to measure fog oil aerosol deposition (Douglas et al. 2006).

To run the simulation, three point sources were used for the release of fog oil aerosol: one for each of the generators mounted on the end HMMWVs and a third to represent the two generators mounted on the middle HMMWV. To determine the rate of oil released from each of these sources, it was assumed that each generator released the same amount of oil per unit time. The four generators used 760 L per 93 minutes or 123 L/hr each. The specific gravity, S , of SGF2 is 0.83–0.93 (Nam et al. 1999), and that of diesel fuel is 0.81–0.89 (Petroleum Product Surveys 1987). The weighted average of these two oils is $S = 0.87$, which gives a release rate for each generator of 107 kg/hr. This value would be the release rate for the two end sources (one fogger operating on each); the release rate for the middle point source would be twice that (two operational foggers on this HMMWV).

SCIPuff allows for either a lognormal or a uniform particle size distribution. For this study, a lognormal distribution was used because this is characteristic of naturally occurring aerosols (Pruppacher and Klett 1940, Jursa 1985). The aerosol size variation is likely quite small because small droplets (less than 10 nm) likely will evaporate, and large particles (greater than 50 microns) will have a high fall velocity (~ 1 m/s or more) and will not travel far (a few meters) before falling to the ground. Muhly (1983) and

Eberhard et al. (1989) reported that the mean droplet size, μ , for SGF2 fog oil aerosols is about 0.5–1 μm , but no value is given for the variance (σ). The addition of diesel fuel likely affects this distribution, but no data exist for the 70:30 SGF2:diesel fuel mix. Therefore values for μ and σ were used as model tuning parameters that were iteratively modified to obtain model results that agreed well with the field data.

Another unknown was the droplet bin sizes. The maximum particle size bin is tied to the upper tail of the lognormal distribution. The minimum bin boundary is constrained by the fall velocity and evaporation of very small droplets. For droplets smaller than 10 nm, they will have a very long residence time in the air (on the order of days to weeks) as a result of their very low fall velocity, such that they are likely to evaporate before they deposit on the ground. Therefore, in the simulation, they are for all intents and purposes a passive scalar that never gets deposited within the domain of interest (~2-km radius from the source). An initial size range of 0.01–50 μm was selected based on the foregoing reasoning. The final range for the upper and lower limits was selected based on the presence or absence of particles of a certain size deposited on the ground in the simulation. If the simulation showed there were no particles deposited in the upper or lower size bins, the “empty” bin was discarded and the remaining range was more finely resolved. This became an iterative process so that the maximum resolution (12 bins) could be provided over the range where there were relevant droplet sizes (see Table 1). For the final droplet size distribution used in the simulations, the resolution of the bin sizes is finer near the center of the distribution and coarser at the upper and lower limits of the size range.

Lacking any information on the decay rate of the droplets during day or night, these were set to zero. As a consequence, it is assumed that there is no evaporation of the droplets over the size range modeled within the computational domain. The albedo, surface roughness, and Bowen ratio were selected based on the ground being covered with snow and the prevailing winter conditions. (Recommended values of Bowen ratio from the SCIPuff online help were used based on reported ambient conditions for each event.)

A limitation to SCIPuff and also HPAC is that they assume that the release is either carried aloft because of buoyancy (the density of release is lower than ambient air, usually due to temperature differences) or that the re-

lease is from a vertical stack, therefore any stack exit velocity (if specified) is directed vertically. Yet, the fog oil generators have their “stacks” or nozzles pointed more or less in the horizontal plane and have high exit velocities (approximately 70 m/s; Policastro et al. 1989). Initial model results suggested that if there is an appreciable misalignment between the ambient wind and the direction that the nozzles point, there can be some disagreement between the measured and predicted oil deposition in the immediate vicinity (50 m or so) of the generators. This was especially noticeable for Event 3. To compensate for this misalignment, a “false” meteorological station was added at the location of the generators with a large wind speed (20 m/s) and an imposed wind direction aligned with the generator nozzles (55° from north). This value of 20 m/s is an estimate of the plume velocity a short distance (about 1 m) from the nozzle exit due to entrainment of the surrounding air into the jet of fog oil exiting the generator. This was computed from $U(x) = 6U_j d/x$ (Pope 2000), where U is the centerline velocity of the jet a distance, x , from the nozzle exit; d is the nozzle diameter (about 4–6 cm for the foggers), and U_j is the jet exit velocity (about 70 m/s). This effectively projects the jet momentum, $(U_j d)^2$, to the grid scale of the computational domain. This wind speed and direction was held constant throughout the simulation. To keep this effect local to the region surrounding the fog oil generators, more meteorological “stations” were added to the domain that all repeated the measured data at the actual met station. The locations of these “mock stations” are shown in Figure 5. SCIPuff interpolates the meteorological data over the domain; the addition of the extra stations helps to keep the interpolated meteorological data correct for the bulk of the domain while allowing for variation near the generators. A complete summary of the input data for simulating Event 3 is given in Table 1.

Event 4 (12 Sept 2002)

This exercise also took place at the Firebird Landing Zone. The air temperature ranged from 10 to 15° C with a cloud cover. Two fog oil generators were mounted on each of two HMMWVs that were spaced about 5 m apart. The outlet nozzles for the generators were pointed in a north-northwesterly direction, and the wind was out of the south-southeast. Both generators on each HMMWV were operated for the duration of the 70-minute exercise, which started at 12:23 pm AST. All four generators used a total of 420 L of SGF2.

During this event, only the wind speed and direction were collected at the met tower (located about 700 m southwest of the release point). However, there appeared to be a problem with the wind direction measurements after the first few minutes of measured data. Because initial measurements of wind direction varied from 150 to 170°, we used a fixed wind direction of 160° throughout the simulation. This aligned the wind direction with the direction the nozzles were pointed (340°).

As with Event 3, a combination of filters, flowers, and leaves was placed downwind of the generators to collect oil deposition on the ground during the exercise. Figure 5 shows the location of the samplers in relationship to the generators (HMMWVs).

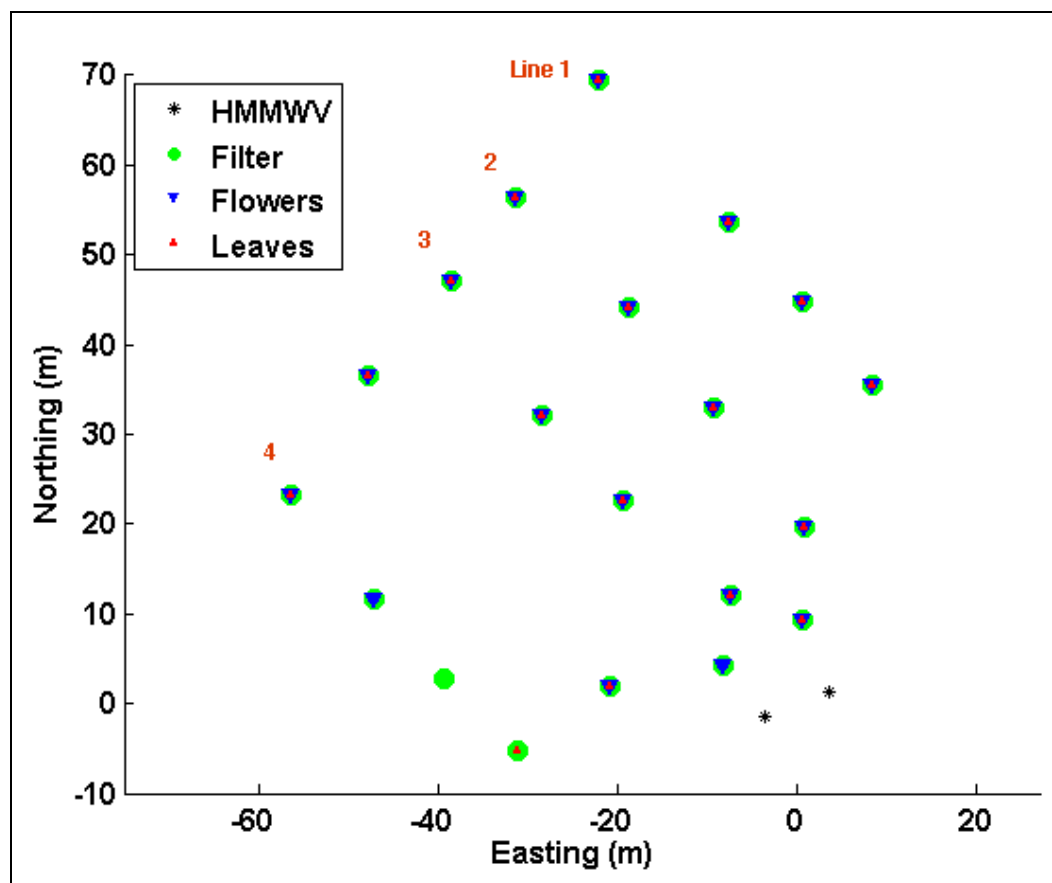


Figure 5. Location of HMMWV-mounted generators and sample locations during Event 4.

Table 1. Summary of input data required for the numerical simulations of Events 3 and 4.

Input data	Event 3	Event 4
Event duration (minutes)	93	70
Average oil density (kg/m ³)	870	880
Minimum aerosol (oil) concentration (kg/m ³)	1×10^{-10}	1×10^{-10}
Number of release points modeled	3	2
Single generator release rate (kg/hr)	107	79.2
Particle size distribution (lognormal)		
	μ (μm) 0.8	1.2
	σ 1.5	2.0
<u>Bin boundaries (μm)</u>	0.075	0.01
	0.1	0.075
	0.3	0.1
	0.5	0.3
	0.7	0.6
	0.8	0.8
	0.9	1
	1.0	2
	2.0	3
	3.0	5
	4.0	15
	5.0	30
	7.5	40
Particle decay rate: day/night (s ⁻¹)	0/0	0/0
Source height above ground (m)	1.5	1.5
Nozzle diameter (m)	0.1	0.1
Meteorological data, surface observations only	RH, WS, DIR from record	WS, DIR from record
Surface roughness, Z_0 (m)	5×10^{-4}	1×10^{-3}
Boundary layer	Calculated	Calculated
Bowen ratio	1.5	0.8
Surface albedo	0.7	0.3
Fractional cloud cover	0	0.8
Large-scale variability	Operational	Operational

Table 1 includes a summary of the input data for the simulation of Event 4. In this simulation, two point sources were used for the fog oil release, one for each HMMWV. Because there are two generators per source, the material released at each source is twice the amount given for the generator. Because of the very close alignment of the wind and the nozzle exits during

this exercise, there was no need to use “mock stations” to account for the local effects of the nozzle exit velocity on the lateral plume dispersion. The surface roughness, albedo, and Bowen ratio used for this event were chosen based on a grassy terrain and prevailing summer/fall conditions.

A slightly different particle size distribution was used in this simulation (see Table 1) to achieve good agreement between the model and field data. Two reasons likely impact this need for a different particle size distribution:

1. Differences in air temperature;
2. Differences in fog oil type, SGF2 used during Event 4 vs. the SGF2:diesel mix used in Event 3.

These effects will be discussed in more detail below.

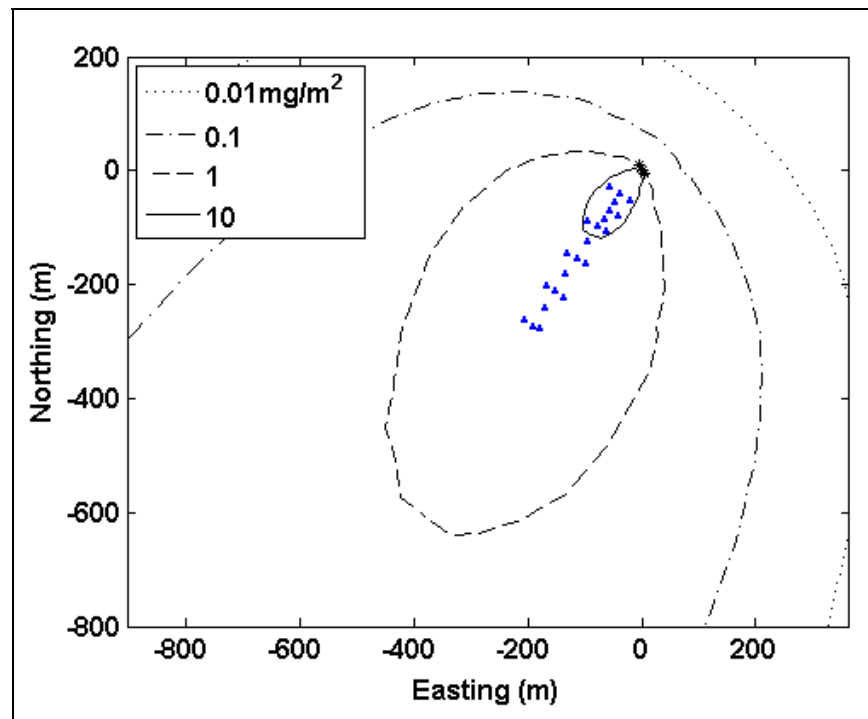
4 Results

Figure 6 shows the model results obtained from SCIPuff for Events 3 and 4. This shows the predicted spatial distribution of the oil fog deposition on the ground at the end of each event. Both of these results show fanning of the fog oil plume, with Event 3 being more pronounced than Event 4. The narrower cone of Event 4 is due to the winds being modeled as coming from a fixed direction.

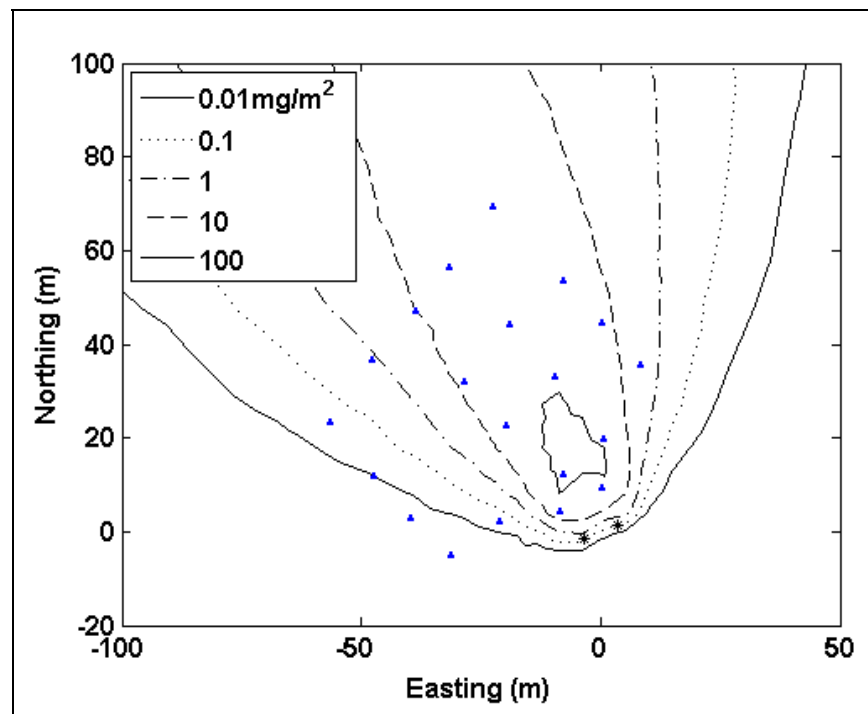
The model results are compared to the field data in Figures 7 (Event 3) and 8 (Event 4). In Figure 7, the comparison is made along each of the three sampler lines, identified in Figure 3, extending out from the fog oil generators. Figure 7 shows that there is generally good agreement between the measured data and the model prediction for all three lines in that the overall trend in the data and the magnitude of the deposition are preserved; however, there is clearly some disagreement in the details. There are likely two main reasons for this: (1) there is a lot of scatter in the data and (2) the limitations of the model used to simulate the event. These issues will be addressed below.

The scatter in the data is especially apparent on Line 2 (the middle pane in Figure 7) where multiple samplers were used at the same location. Figure 7 shows that along this line, near the source, the model and all three sampler types show reasonable agreement. Beyond about 150 m, the flower sampler tends to report a lower deposition than the filter or leaf samplers and shows a monotonic decrease in deposition that agrees best with the model prediction. Yet, based on reported field observations (Douglas et al. 2006), the “spikes” in deposition seen in the middle pane of Figure 7 for the filter and leaf samplers are consistent with observations of the plume during the event. During this event, the fog oil plume exhibited what is known as “looping¹” behavior, wherein the plume meanders up and down in the vertical direction as a result of instability in the lower atmosphere (e.g., Figure 9). As the lower lobes of the looping plume touch the ground, they bring a high aerosol concentration to the surface, producing a locally elevated deposition. Figure 10 is a picture taken during Event 3 that shows a lobe of the looping plume touching the ground.

¹ This looping behavior was described as “bouncing” by Douglas et al. (2006).



a. Event 3.



b. Event 4.

Figure 6. Predicted spatial distribution of deposited fog oil during Events 3 and 4. Locations of the releases (*) and sample points (blue triangles) are also plotted.

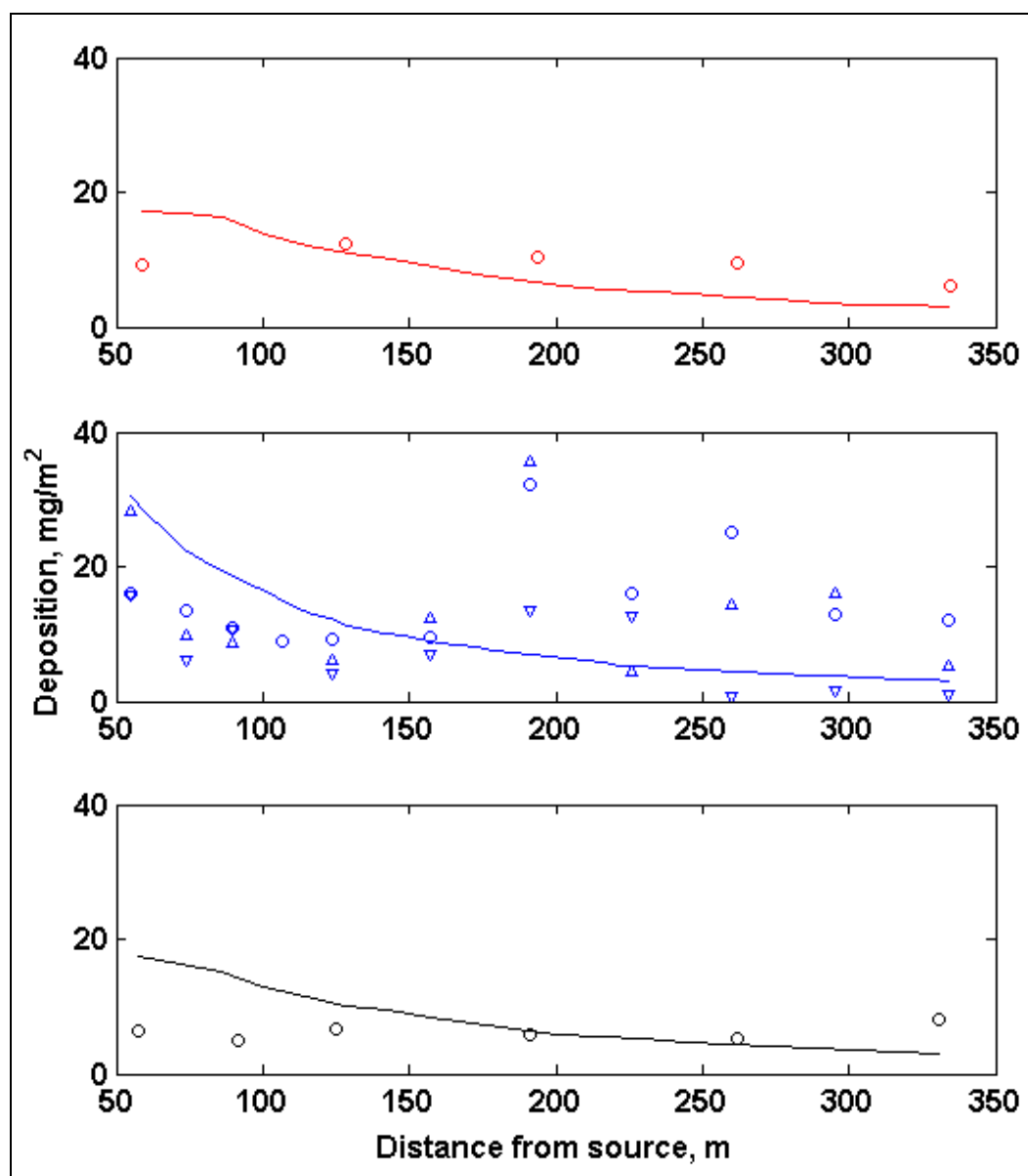


Figure 7. Comparison of predicted fog oil deposition to measured field data for Event 3 (31 Jan 2002). The three panes correspond to the three linear sections taken at the site and numbered in Figure 3. When facing the generators, the top pane is the left line (1) and the bottom pane is the right line (3). The middle pane is the middle line (2). All three sampler types are shown: filter (o), flower (blue upside-down triangle), and leaf (blue triangle).

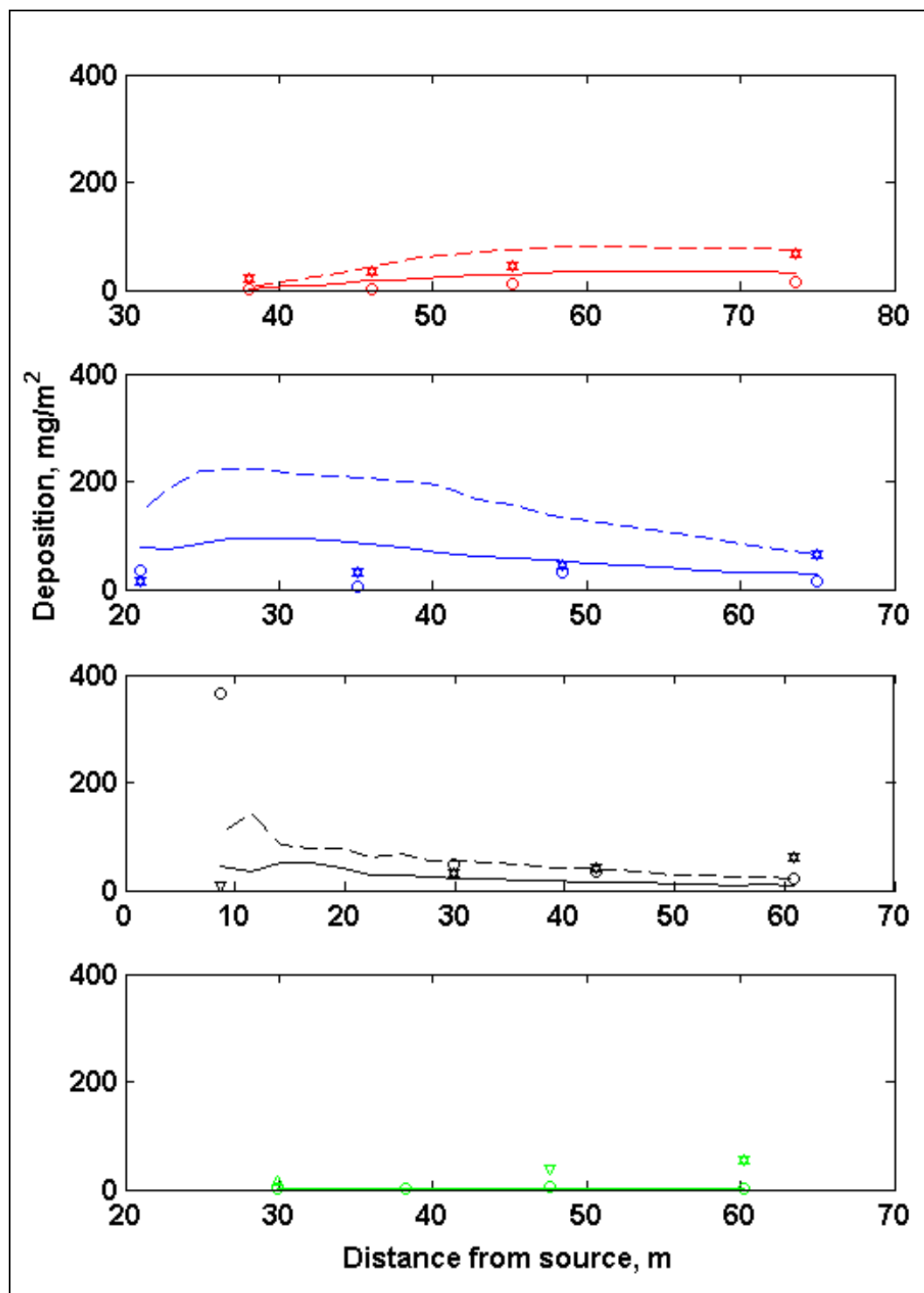
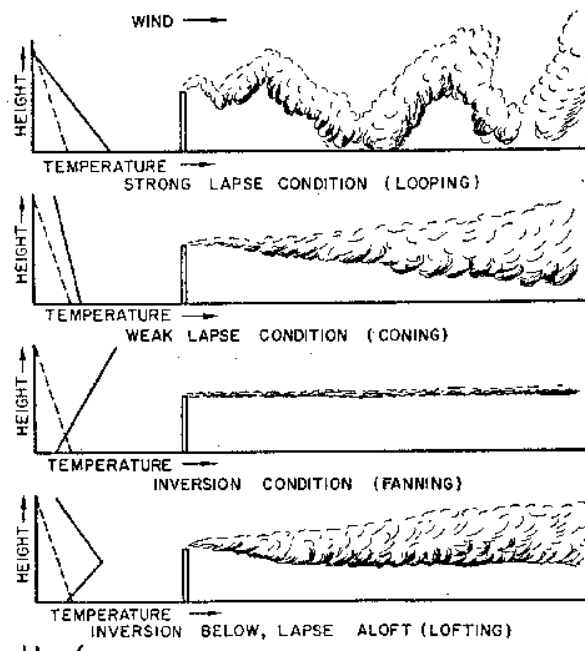


Figure 8. Comparison of predicted fog oil deposition to measured field data for Event 4 (12 Sept 2002). Both the predicted deposition on the surface (-) and the predicted deposition at 0.25 m (- -) above the surface are shown. The four panes correspond to four linear sections taken at the site and numbered in Figure 5. When facing the generators, the top pane is the left line (1) and the bottom pane is the right line (4). All three sampler types are shown: filter (o), flower (upside down triangles), and leaf (triangles).



a. Various plumes.

(<http://www.iitap.iastate.edu/qcp/acid/images/plume.gif>)



b. Plume showing mild looping.

Figure 9. Examples of a looping plume exiting a smokestack.



Figure 10. Fog oil plume from Event 3, during which looping was observed. A lower lobe of the looping plume can be seen touching the ground at the left side of the photo. (Photo by Thomas Douglas, ERDC/CRREL.)

The spikes in the deposition shown in the middle pane of Figure 7 appear to be a result of the looping witnessed during the fogging event. The reason for the discrepancy in the measured data—where the filter and leaf samplers showed elevated surface deposition due to the plume “bouncing” along the surface while the flower samplers did not—is not clear. Yet, it is not surprising that SCIPuff did not capture this looping phenomenon in the simulation. This is a combined result of a) the limitations associated with the input data and b) the model used to simulate the event. First, the supplied surface meteorological data was given only at one point in the domain and therefore was too coarse (temporally and spatially) to resolve the atmospheric instability that causes looping. Additional met sites and detailed velocity profile data would be needed to resolve this phenomenon. Furthermore, SCIPuff primarily models turbulent diffusion, a smoothly varying process that is characterized by a Gaussian spread, and therefore by nature does not capture rapid fluctuations. To model the detailed flow structure that gives rise to looping would require a more sophisticated—and more computationally intense—turbulence modeling scheme, such as the Large Eddy Simulation method. Regardless, the simulation of Event 3 seems to capture the overall trends well in spite of the limitations of the available meteorological data and SCIPuff.

During Event 4, the plume was much more diffusive and no looping was observed. As a result, there was a more smoothly varying deposition field, as captured in Figure 8. During this event, the deposition on the filters was generally lower than that of the leaves or flowers. Douglas et al. (2006) reported that the measured deposition for the leaves and flowers was consistently 60% higher than the surface filter measurements for all of the events except Event 3. This stands to reason because the leaves and flowers were on stalks that placed them up into the air, protruding into the plume, whereas the filters were placed flat on the ground. The one notable exception to this is the high deposition recorded on the filter near the source in Line 3 (next to bottom pane of Figure 8); this shows a radical departure from the flower sample. The reason for this departure is not clear.

Figure 8 also provides a comparison of the field data to the model results for Event 4. Figure 8 includes plots of the predicted deposition at the ground surface (solid line) and at an elevation of 0.25 m (dashed line). These approximately correspond to deposition on the ground-mounted filter and the flower/leaf that are on a stalk¹, respectively. Generally, the agreement is quite good for all but Line 2. In particular, the deposition to the ground predicted by the model splits the difference between the filter and flower/leaf data in Line 1, has good agreement with almost all of the data in Line 3, and for Line 4 agrees well with the filter data only. The model prediction for deposition on the flower/leaf samples at about 0.25 m seems to replicate the trends for Lines 1 and 3. However, for Line 4, the measured deposition is much higher than the predicted deposition at the 0.25-m height. This may be caused by the wind being modeled as coming from a fixed direction. Natural variability in the wind direction will increase lateral dispersion of the fog oil droplets, and thereby would increase the deposition on the samplers along Line 4.

Along Line 2, the model predicts a deposition on the ground that is about the right order of magnitude, but the data and model trend the opposite way. There is no clear explanation for this trend, though some errors resulting from imposing a fixed wind direction in the simulation are expected. Regardless, the overall agreement between the model and data for both events is remarkably good.

¹ The flowers and leaves protruded approximately 0.1–0.4 m up into the flow, so a deposition height of 0.25 m is a rough average height for these samplers.

From the foregoing discussion it is clear that the predictive capability of SCIPuff for this application is partially hampered as a result of the accuracy of the input data (meteorological and other data) and lack of easily being able to specify the horizontal momentum at the nozzle. The input data compiled in Table 1 are a combination of reported information and best estimates based on the conditions reported during the test. Information such as surface albedo, cloud cover, Bowen ratio, and surface roughness all affect the estimation of atmospheric turbulent mixing and can have a profound effect on surface deposition of the fog oil. Therefore, it is important to get a good estimate of these values to expect accurate model results. Generally, however, these can be determined to a good approximation using standard tables for seasonal atmospheric conditions and land cover data. Yet, the two biggest factors influencing surface deposition are the wind data (speed and direction) and droplet size distribution. Meteorological data can normally be obtained after the fact (via local first-order stations or on-site met stations) or via forecast data. However, getting a good estimate of the droplet size distribution is not trivial and became the biggest “tuning knob” in these simulations, and requires more attention.

The fog oil aerosol mean droplet size used for modeling was about 0.5–1 μm (Muhly 1983, Eberhard et al. 1989) and SCIPuff provides a basic assumption that the distribution was lognormal. Yet small changes in μ ($\pm 0.2 \mu\text{m}$) had a significant effect on fog oil aerosol deposition (Figure 11); changes in σ also changed the predicted deposition amount (Figure 12), though to a lesser extent. From Figures 11 and 12 it is clear that increasing the mean droplet size and increasing the non-uniformity of the size distribution (σ) increases the amount of fog oil deposited on the ground. This stands to reason, because larger droplets have a higher fall velocity and will deposit on the ground sooner (i.e., closer to the source); increasing μ and σ makes more large droplets available in the plume. Because of the extreme sensitivity of these two parameters on the model outcome, clearly more information about the droplet size distribution for fog oil and 70:30 SGF2:diesel fuel mix aerosols is required to provide a true predictive capability for modeling the deposition of fog oil using SCIPuff or other transport models.

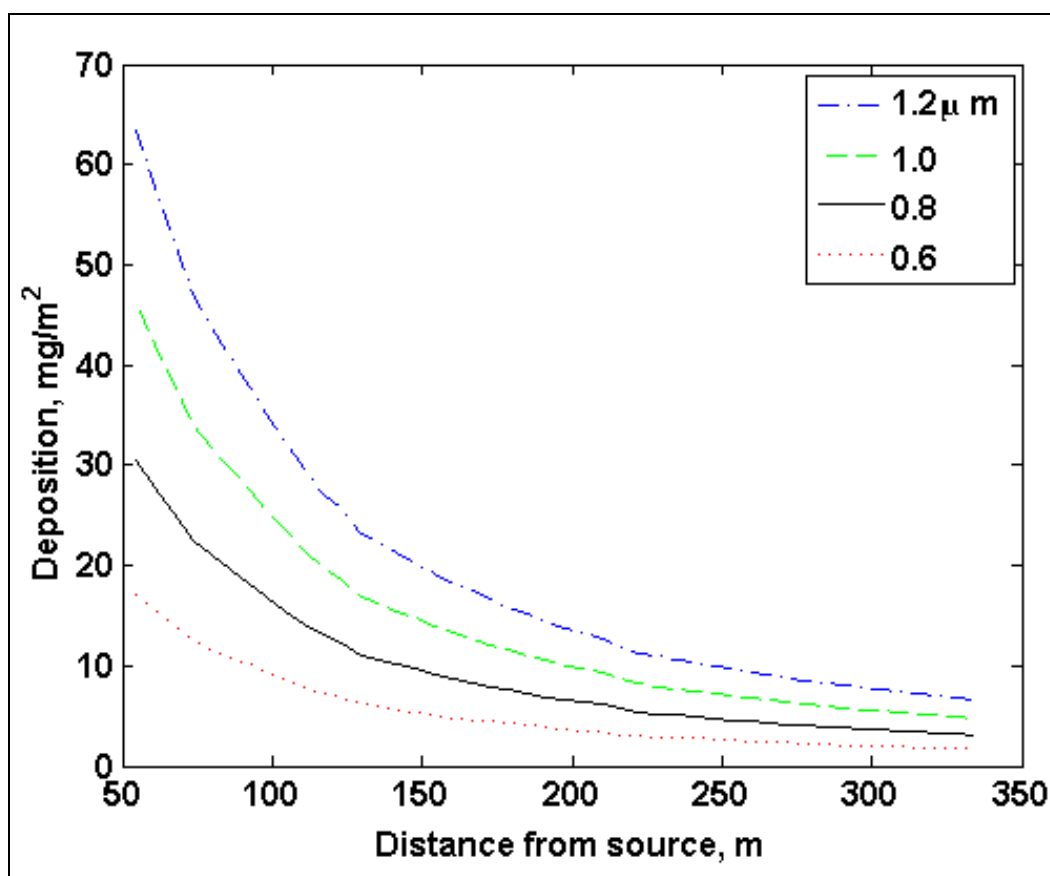


Figure 11. Effect of mean droplet size on fog oil deposition along Line 2 of Event 3. Each line represents a different mean value in droplet size.

The two major differences between these two events were air temperature and the fog oil mixture; therefore, the effects of temperature and fog oil composition on droplet size need to be considered. In this study, winter and late summer conditions prevailed for Events 3 and 4, respectively. Also, two fog oil mixtures were used, 70:30 SGF2:diesel and SGF2 only, respectively. Yet the fog oil generator operator's manual (Army 1985) specifies a range of other fog oil mixtures, dependent on ambient air temperature, with mixtures of 75:25, 60:40, and 50:50 of SGF2:kerosine recommended as the temperature decreases from 0° C to -40° C. Because these recommendations are standard operational procedures for fog oil generators in cold climates, these other mixtures and temperatures should also be included in future studies to determine the correct droplet size distribution for a range of conditions.

In the absence of detailed information about the droplet size distribution, SCIPuff can be used as a predictive model provided it is understood that there is an error associated with the answer obtained. If the mean droplet

size of $1\text{ }\mu\text{m}$ that was reported by Eberhard et al. (1989) is used, the deposition is over-predicted for Event 3 and under-predicted for Event 4. Figure 11 gives some sense of the error that can be expected. The deposition predicted for Event 3 using a mean size of $1\text{ }\mu\text{m}$ gives a deposition that is 50–75% higher than when using the mean size of $0.8\text{ }\mu\text{m}$ that gave a best fit to the data. Taking this together with the effects of the uncertainty in the size distribution, σ , one can expect a factor of two (or more) error in the model prediction by simply using a fixed mean droplet size of $1\text{ }\mu\text{m}$ and $\sigma = 1.7$ (where this value of σ is an average between the two cases simulated) for all training conditions. Using this approximation for droplet size distribution, one might expect the prediction to be correct within one order of magnitude, but no better than that.

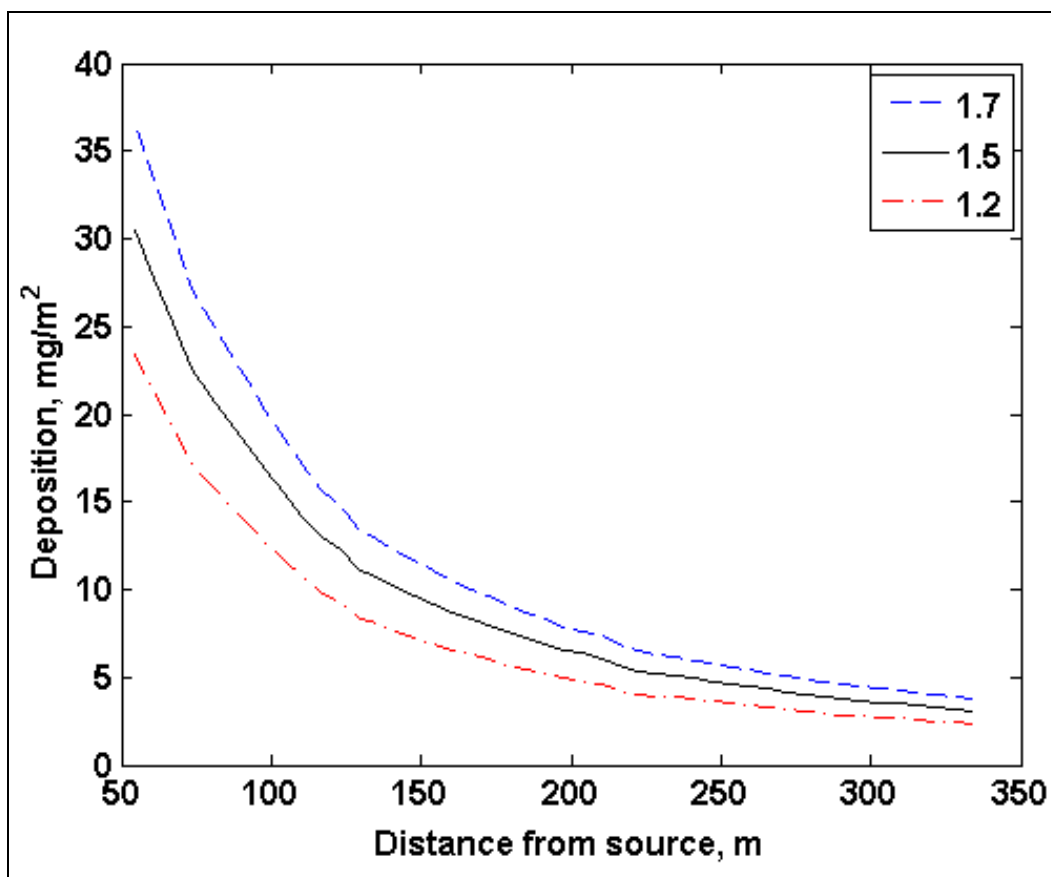


Figure 12. Effect of changing the standard deviation, σ , of the droplet size distribution on the predicted amount of fog oil deposited on the ground. This is also demonstrated for Line 2 of Event 3. Each line represents a different value of σ for the droplet size distribution.

5 Conclusions and Recommendations

In this study, the deposition of fog oil aerosol on the ground during two military training exercises was simulated. The computer model used to simulate these events was SCIPuff, which is used to model the convection–diffusion transport equation with Lagrangian puffs of aerosol to track the movement of an aerosol contaminant within the domain of interest. SCIPuff is the computational engine used in the HPAC hazard assessment software suite.

Using measured meteorological data and other observed information, a hindcast was performed for these two events. Most of the relevant information needed to set up the model was readily obtainable via historical data or look-up tables for typical conditions. However, the droplet size distribution for the fog oil aerosol and the 70:30 SGF2:diesel fuel aerosol needed to be determined by trial and error, and varied between the two simulated events. The variation in droplet size distribution may be explained by temperature and seasonal differences between the two events, as well as differences in the fog oil used in each event. One event was carried out in the wintertime and diesel was mixed with the SGF2, whereas the other event took place in the early fall and only SGF2 was used.

Once a suitable droplet size distribution was determined, the agreement between the model and field data was quite good. The overall deposition pattern was captured well and the amount of fog oil deposition was predicted to generally within an order of magnitude or better. It may be possible to improve the predictive capability by using more sophisticated models, such as Large-Eddy Simulation (LES), that capture the turbulent structure of the flow. However, such models are much more computationally demanding than SCIPuff—requiring days of computer time and/or high-performance computing resources vs. a few hours on a desktop computer to run SCIPuff—and depending on the need, the increased accuracy may not be offset by the extra time required to obtain an answer.

The biggest unknown in using SCIPuff to predict fog oil deposition is determining the droplet size distribution. Further work is needed to understand the appropriate particle size distribution under a range of meteorological conditions to improve the accuracy of this model. Using lognormal

distribution with a mean droplet size of $1\text{ }\mu\text{m}$ and $\sigma = 1.7$, one can expect to predict the fog oil deposition on the ground to within an order of magnitude or so. Improved accuracy might be achieved if seasonal variability were accounted for by using a lognormal distribution with $\mu = 1.2\text{ }\mu\text{m}$ and $\sigma = 2.0$ for summer conditions (with SGF2 only), whereas for winter conditions (with a 70:30 SGF2:diesel mix), $\mu = 0.8\text{ }\mu\text{m}$ and $\sigma = 1.5$ is recommended.

References

- Army (1985) Operator's Manual: Generator, Smoke, Mechanical: Pulse Jet, M3A4 (1040-01-143-9506), TM 3-1040-276-10, Headquarters, Department of Army, September.
- Douglas, T.A., J.B. Johnson, C.M. Collins, C.M. Reynolds, K.L. Foley, L.B. Perry, A.B. Gelvin, and S.E. Hardy (2006) Assessing the Fog Oil Deposition to Simulated Plant Surfaces During Military Training. US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, Technical Report ERDC/CRREL TR-06-19.
- Eberhard, W.L., R.E. Cupp, and N.L. Abshire (1989) Conservation properties of oil fog used as an atmospheric tracer. *Atmospheric Environment*, **23**:8, 1855–1861.
- Jursa, A.S. (1985) Handbook of Geophysics and the Space Environment, 4th Ed. Final Report, Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts.
- Muhly, R.L. (1983) Programmatic Life Cycle Environmental Assessment for Smoke/ Obscurants, Volume 1: Fog oil, Diesel Fuels, and Polyethylene Glycol (PEG 200). Chemical Research & Development Center, Aberdeen Proving Ground, Maryland, July.
- Nam, S., M.E. Walsh, J. Day, and K.A. Reinbold (1999) Methods for Field Studies of the Effects of Military Smokes, Obscurants, and Riot Control Agents on Threatened and Endangered Species, Volume 4: Chemical Analytical Methods. US Army Construction Research Engineering Laboratory, Champaign, Illinois, Technical Report 99/56, July.
- Petroleum Product Surveys (1987) Diesel Fuel Oils, 1987. Petroleum Product Surveys, National Institute for Petroleum and Energy Research, October.
- Policastro, A.J., D.M. Maloney, W.E. Dunn, J.C. Liljegren, and G.E. DeVaul (1989) Evaluation of Atmospheric Dispersion Models for Fog-Oil Smoke Dispersion, Field Measurement and Model Evaluation Program for the Assessment of the Environmental Effects of Military Smokes. US Army Biomedical Research and Development Laboratory, Fort Detrick, Frederick, Maryland.
- Pope, S.B. (2000) *Turbulent Flows*. Cambridge: Cambridge University Press, pp. 101–102.
- Pruppacher, H.R., and J.D. Klett (1940) *Microphysics of Clouds and Precipitation*, 2nd Ed. Dordrecht, The Netherlands: Kluwer Academic Publishers.
- Sykes, R.I., and R.S. Gabruk (1997) A second-order closure model for the effect of average time on turbulent plume dispersion. *Journal of Applied Meteorology*, **36**, 1038–1045.
- Sykes, R.I., C.P. Cerasoli, and D.S. Henn (1999) The representation of dynamic flow effects in a Lagrangian puff dispersion model. *Journal of Hazardous Materials*, **64**(3): 223–247.

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14. ABSTRACT In this study we evaluate the ability to simulate deposition of a fog oil (Standard Grade Fuel Number 2 or SGF2) obscurant on the ground using the SCIPuff aerosol transport model. Model results are compared to actual deposition of fog oil measure on the ground during two military training exercises in Alaska. One exercise took place during late summer; the other occurred during midwinter. The results show that SCIPuff can be used to give a general picture of the spatial deposition of fog oil by successfully reproducing the overall trends of the field data and predicting the deposition to within an order of magnitude or better. Improved predictive capability might be realized using more sophisticated flow solvers employing computational fluid dynamics (CFD) and large eddy simulation (LES) methods. However, use of CFD and LES would increase significantly the computational expense required. This study shows that model results are sensitive to the aerosol droplet size distribution used and that there appears to be some dependency of this size distribution on air temperature or fog oil used (pure SGF2 vs. SGF2:diesel mix). To improve the predictive modeling capability of aerosol transport models, it is recommended that further work be accomplished to quantify the environmental and mixture effects on the airborne fog oil droplet size distribution. In lieu of this information, an estimate of the deposition, good to within about an order of magnitude, can be obtained using a lognormal droplet size distribution with a mean droplet size of 1 µm and variance of 1.7.					
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